pressure waveform on an oscilloscope. During a right ventricular heart catheterization, pressures in the right atrium, right ventricle, and pulmonary artery are routinely measured in this manner. The catheter can then be advanced further until it *wedges* in the distal pulmonary artery. The transmitted pressure measured in this location originates from the pulmonary venous system and is known as the *pulmonary capillary wedge pressure.* In the absence of pulmonary venous disease, the pulmonary capillary wedge pressure reflects left atrial pressure, and if no significant mitral valve pathologic condition exists, it reflects left ventricular diastolic pressure. A more direct method of obtaining left ventricular filling pressures is to advance an arterial catheter into the left ventricular cavity. With these two methods of obtaining intracardiac pressures, each chamber of the heart can be assessed and the gradients across any of the valves determined (Fig. 4-15).

Cardiac output can be determined by one of two widely accepted methods: the Fick oxygen method and the indicator dilution technique. The basis of the Fick method is that total uptake or release of a substance by an organ is equal to the product of blood flow to that organ and the concentration difference of that substance between the arterial and venous circulation of that organ. If this method is applied to the lungs, the substance released into the blood is oxygen; if no intrapulmonary shunts exist, pulmonary blood flow is equal to systemic blood flow or cardiac output. The cardiac output can be determined by the following equation:

$$\text{Cardiac output} = \text{oxygen consumption} \div (\text{arterial oxygen content} - \text{venous oxygen content})$$

Oxygen consumption is measured in milliliters per minute by collecting the patient's expired air over a known period while simultaneously measuring oxygen saturation in a sample of arterial and mixed venous blood (i.e., arterial and venous oxygen content, respectively, measured in milliliters per liter). The cardiac output is expressed in liters per minute and then corrected for body surface area (i.e., cardiac index). The normal range of cardiac index is 2.6 to 4.2 $L/min/m^2$. Cardiac output can also be determined by the indicator dilution technique, which most commonly uses cold saline as the indicator. With this method, cold saline is injected into the blood, and the resulting temperature change *downstream* is monitored. This action generates a curve in which temperature change is plotted over time, and the area under the curve represents cardiac output.

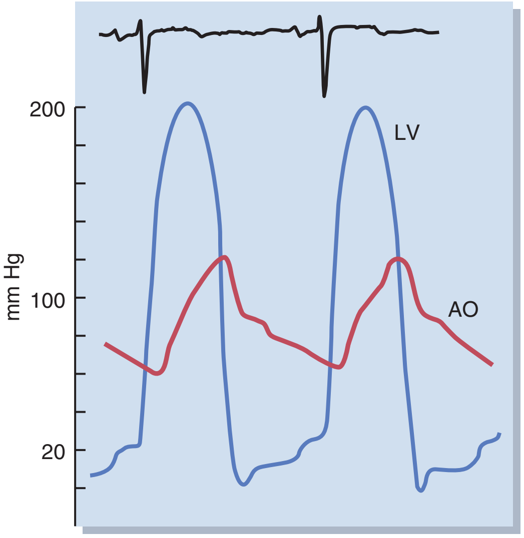

FIGURE 4-15 Electrocardiographic tracing and left ventricular (LV) and aortic (AO) pressure curves in a patient with aortic stenosis. A pressure gradient occurs across the aortic valve during systole.

Detection and localization of intracardiac shunts can be performed by sequential measurement of oxygen saturation in the venous system, right side of the heart, and two main pulmonary arteries. In patients with left-to-right shunt flow, an increase in oxygen *step-up* (i.e., saturation increase from one chamber to the successive chamber) occurs as arterial blood mixes with venous blood. By using the Fick method for calculating blood flow in the pulmonary and systemic systems, the shunt ratio can be calculated. Noninvasive approaches have largely supplanted catheterization laboratory assessment of shunts.

Left ventricular size, wall motion, and ejection fraction can be accurately assessed by injecting contrast into the left ventricle (i.e., left ventriculography). Aortic and mitral valve insufficiency can be qualitatively assessed during angiography by observing the reflux of contrast medium into the left ventricle and left atrium, respectively. The degree of valvular stenosis can be determined by measuring pressure gradients across the valve and determining cardiac output (i.e., Gorlin formula).

The coronary anatomy can be defined by injecting contrast medium into the coronary tree. Atherosclerotic lesions appear as narrowing of the internal diameter (lumen) of the vessel. A hemodynamically important stenosis is defined as 70% or more narrowing of the luminal diameter. However, the hemodynamic significance of a lesion can be underestimated by coronary angiography, particularly when the atherosclerotic plaque is eccentric or elongated. Intravascular ultrasound, Doppler flow wires, or miniaturized pressure sensors can be used during invasive procedures to help evaluate the severity or estimate the physiologic significance of intermediate lesions.

Biopsy of the ventricular endomyocardium can be performed during cardiac catheterization. With this technique, a bioptome is introduced into the venous system through the right internal jugular vein and guided into the right ventricle by fluoroscopy. Small samples of the endocardium are taken for histologic evaluation. The primary indication for endomyocardial biopsy is the diagnosis of rejection after cardiac transplantation and documentation of cardiac amyloidosis; however, endomyocardial biopsy may have some use in diagnosing specific etiologic agents responsible for myocarditis.

Right Ventricular Heart Catheterization

A right ventricular heart catheterization can be performed at the bedside with a balloon-tipped pulmonary artery (Swan-Ganz) catheter. This technique enables serial measurements of right atrial, pulmonary artery, and pulmonary capillary wedge pressures and cardiac output by thermodilution (Fig. 4-16). These measurements may be useful in monitoring the response to various treatments, such as diuretic therapy, inotropic agents, and vasopressors (Table 4-4). The pulmonary artery catheter is most useful in the critically ill patient for assessing volume status and differentiating cardiogenic from noncardiogenic pulmonary edema. However, several papers have suggested no